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SPECTRAL AND SPATIAL RESOLUTION OF THE 12.8μ Ne II EMISSION
FROM THE GALACTIC CENTER*

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ABSTRACT

High-resolution spectra of the Ne II 12.8μ fine-structure line in emission from the galactic center cloud Sgr A West show a line-center LSR radial velocity of $+75 \pm 20 \text{ km s}^{-1}$ and a velocity dispersion of about 200 km s^{-1} . The line has been observed with spectral resolution as high as 0.10 cm^{-1} and spatial resolution as high as $8''$. This appears to provide a direct measurement of conditions in the $45''$ ionized region at the galactic center. The radial velocity and dispersion are more-or-less independent of position and indicate that events as recent as the last 10^4 years have given the ionized gas a systematic motion with respect to the massive stellar component of material at the galactic center. An upper limit of $\sim 4 \times 10^6 M_{\odot}$ for the mass within 0.8 parsecs of the galactic center is obtained from the velocity dispersion.

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Introduction

The thermal radio continuum source Sgr A West (Downes and Martin 1971) is generally thought to be at the center of the galaxy. This radio source, approximately 45" in diameter, (Balick and Sanders 1974) is coincident with strong continuum infrared radiation (Becklin and Neugebauer 1968). Observations indicate a cloud containing approximately $100 M_{\odot}$ of ionized gas and somewhat greater than $10^6 M_{\odot}$ of stars whose radiation is obscured by several tens of magnitudes of visual extinction (Rieke and Low 1973). Both the radio and IR continua exhibit considerable spatial structure, with features as yet unresolved (Balick and Brown 1974; Becklin and Neugebauer 1975, hereafter BN). Several radio recombination lines have been detected toward Sgr A West with angular resolution not better than a few arc minutes (Lockman and Gordon 1973; Brown and Balick 1973; Pauls, Mezger and Churchwell 1974). Although there is evidence that some of the detected recombination line emission originates in the central cloud, the angular extent of line emission is considerably larger than 45". Furthermore, the possibility exists that the detected recombination line spectra are affected and perhaps dominated by interstellar amplification (Dupree and Goldberg 1969; Brown and Gómez-González 1975). Consequently, the physical relationship between the material responsible for the thermal radio continuum flux and that responsible for the observed recombination line emission is uncertain.

Aitken, Jones and Penman (1974) have reported detection of the 12.8μ fine-structure line of Ne II in emission from Sgr A West. Additional observations have since been made by Willner (1975) and Bregman and Rank (1975). Although these observations, made with resolution not higher than several wavenumbers, do not provide detailed spectral information, a sizable amount of information on the spatial distribution of Ne II has been obtained. The results indicate that the Ne II is extended over a region which is roughly coincident with the thermal radio continuum flux from Sgr A West. Unlike the radio molecular and recombination lines, it can be reasonably assumed that the neon emission actually originates in Sgr A West and comes from the same ionized cloud that is responsible for the thermal radio continuum.

We report here high spectral resolution observations of the Ne II 12.8μ line from Sgr A West. The emission has been measured in various parts of the cloud with spectral resolution as high as 0.10 cm^{-1} and spatial resolution as high as $8''$. In all positions examined, it is found that the peak emission corresponds to a radial velocity of $+75 \pm 20 \text{ km s}^{-1}$ with respect to the local standard of rest (LSR). Several possible explanations for this result have been investigated. It seems most likely that the observed frequency of peak emission represents an actual Doppler shift and is evidence for organized motion of the gas component of the galactic center cloud with respect to the massive stellar component.

Observations

The observations were made during April and May, 1975 using a tandem scanning Fabry-Perot interferometer mounted at the Coudé focus of the Cerro Tololo Inter-American Observatory 1.5 m telescope. Additional observations were made during July, 1975 using the Lick Observatory 3.05 m telescope. The spectrometer has been described in detail by Geballe (1974). Four spectra are shown in Figure 1. The three solid-line spectra were obtained with resolution of 0.30 cm^{-1} (corresponding to a Doppler velocity width of 114 km s^{-1}) and with a rectangular field of view $16'' \times 31''$ centered to the north, on, and to the south of the 10μ source IRS 1 (BN). The dashed-line spectrum was obtained with 0.10 cm^{-1} (38 km s^{-1}) resolution in the central beam position. Spectra not shown here have also been obtained of $16'' \times 31''$ regions to the east and to the west of the central position, of several $8''$ circular regions in and about the central rectangular region, and of a $6'' \times 12''$ region to the north of center. These various positions and beam orientations are shown in Figure 2 superimposed on the 10μ contour map of Becklin and Neugebauer. Rectangular beam orientations are only approximately represented, since the Coudé field typically rotated about 15° during an observation. The spectra not presented in Figure 1, although generally of poorer quality, show the same red-shift and breadth as those which are presented. The Ne II rest frequency of $780.43 \pm .03 \text{ cm}^{-1}$ has been obtained from observations of the line in various galactic H II regions and the planetary nebula BD + $30^\circ 3639$,

each of which has a known radial velocity (Wollman et al, 1975a, 1975b). A summary of the integrated fluxes obtained in the various beam positions is given in Table 1.

Discussion

The most interesting features common to all the spectra are the substantial redshift of the peak emission and the similarly large breadth of the line. The peak emission has approximately the same redshift in all beam positions. Since it is commonly believed that the local standard of rest has at most a small radial velocity component with respect to the galactic center, it is surprising to find a large average radial velocity for the ionized gas component of what is thought to be a massive cloud lying at the galactic center. We have considered a variety of possible explanations which are discussed briefly below.

The fact that the line profile seems to be essentially the same in all beam positions where detected eliminates certain possibilities such as overall rotation, expansion, or collapse as primarily responsible for the observed redshift. In any of these cases, one would expect to see variations of the line profile with position. In addition, such an explanation leaves unanswered the question of why only redshifted material, and not the corresponding blue-shifted material, is seen. Continuum absorption at 12.8μ by dust within the cloud might in principle make the near side of the cloud more visible than the far side, and thus

produce a non-zero average radial velocity for the material seen. However, comparison of the 2μ and 10μ continuum fluxes implies that the 12.8μ optical depth of the dust within the cloud is much less than unity (BN).

Another possibility for producing the observed line profile is absorption of the blue side of the line by material between the sun and the galactic center. This might be done by molecules, the most promising perhaps being NH_3 , which does have several transitions that might contribute to such an effect. However, lower resolution spectra of Sgr A West near 10μ , including the region of the strong Q-branches of the ν_2 ammonia bands, place a limit on the column density of NH_3 which is far below that required to affect the shape of the Ne II line (Bregman and Rank 1975). It is also conceivable that intervening Ne II is itself responsible for absorption of the blue side of the line. Since the upper state of the fine structure transition is collisionally populated, the excitation temperature is low in a low-density environment. An adequate column density of Ne II might therefore absorb radiation from the galactic center. Various methods of estimating the column density of ionized material between the Sun and the galactic center indicate that absorption by intervening Ne II can be responsible for at most minor modifications of the profile of the line.

One might consider that the velocity profile of Ne II is not characteristic of the gas as a whole. This is suggested by the fact that the radio recombination line

profiles peak very near $V_{\text{LSR}} = 0$. However, as pointed out in the introduction, the observed profiles of the recombination lines may be determined primarily by intervening material. In addition, the total integrated Ne II flux is consistent with assuming that the observed Ne II represents a substantial fraction of the neon present in the ionized cloud at the galactic center (Aitken et al, 1974). It seems highly unlikely that the Ne II would have a velocity distribution very unlike the rest of the ionized gas, particularly since the same distribution is seen in different parts of the cloud. High-resolution observations of other IR fine-structure lines such as S III (18.7μ), S IV (10.5μ), and Ar III (9.0μ), would provide additional information on this and other aspects of the galactic center material.

The observed redshift might simply be explained as motion of the solar neighborhood rather than a peculiarity of the galactic center. Clube (1973) has suggested that the stellar proper motions are consistent with a model of galactic motion which includes expansion as well as rotation. The indicated expansion velocity for the solar neighborhood is 75 km s^{-1} , in good agreement with the observed radial velocity of the Ne II line. However, other radial velocity surveys indicate that the galactic motion is essentially all rotational and that any radial component of the LSR with respect to the galactic center is small (Oort 1965; Minkowski 1965; Kerr 1962). Hence a large radial velocity of the solar neighborhood with respect to the galactic center seems quite unlikely,

although the observed redshift of the Ne II line indicates that further consideration of this possibility is warranted.

Elimination of the foregoing possibilities leaves it most likely that the observed profile of the Ne II line reflects the actual physical state of the ionized gas in the galactic center. It is important to note in this regard that for electron densities below $\sim 4 \times 10^5 \text{ cm}^{-3}$, the Ne II emission is proportional to the square of the gas density. Thus, the line profile can be a result of some combination of systematic velocity-dependent density variations in the cloud and a non-zero average radial velocity with respect to the LSR.

The center of mass of galactic center material is dominated by its stellar component and presumably has no more than a small radial velocity with respect to the LSR. However, motion of the gas component of the cloud with respect to the stellar component is less unlikely than it might at first appear to be. One reason for this is that the gas is a very small fraction of the total mass of material at the galactic center. Also, although the gravitational potential of the total stellar mass may be a dominant factor in determining the dynamics of the gas, the sum of the gravitational cross-sections of individual stars is relatively small. Consequently, once in motion, it is possible for the gas to move in an organized fashion with respect to the stars.

The time required to travel the radius of the Sgr A West cloud at a velocity of 75 km s^{-1} is about 10^4 years. Since the neon emission coincides so well with the 2μ continuum flux (BN), this is a reasonable upper limit to the time elapsed since the peculiar velocity was imparted to the cloud. With a recent violent event therefore in mind, it is interesting to note the presence of the more extended, non-thermal radio source Sgr A East (Downes and Martin 1971), which might be a supernova remnant. Molecular emission and absorption associated with the immediate vicinity of this source are also redshifted, with velocities ranging between approximately $+30 \text{ km s}^{-1}$ and $+90 \text{ km s}^{-1}$ (cf. Oort 1974).

If the velocity dispersion of the Ne II is used to calculate the total mass at the galactic center from the virial theorem, the mass obtained is about $4 \times 10^6 M_{\odot}$. This is comparable to estimates made from the infrared luminosity (Becklin and Neugebauer 1968), and indicates that the mass-luminosity ratio for material in the galactic center is not very peculiar. Because of rapid decay of turbulence, the gas cannot be expected to obey the virial theorem in the gravitational field at the galactic center. Furthermore, its peculiar motion shows that the dynamics of the ionized gas is not entirely dominated by this field; the velocity dispersion may be due to some completely different cause. Nevertheless, this dispersion should be at least as great as that which results from variations in the gravitational potential, so that $4 \times 10^6 M_{\odot}$ probably represents a reasonable estimate of the upper limit to the total mass

within the angular diameter $45''$ (~ 1.6 pc) about the galactic center.

The suggestion has been made by Becklin and Neugebauer (1975) that several of the 10μ sources might be luminous planetary nebulae. However, it can be seen from Figure 2 and Table 1 that the Ne II is more widely and uniformly distributed than the 10μ continuum radiation. It appears that the centroid of the Ne II emission is displaced slightly to the east of the 10μ ridge. This and the peculiar velocity profile of the Ne II indicate that it does not reside predominantly in planetary nebulae. On the other hand, more highly ionized states such as S IV would be expected to dominate the IR line spectra of luminous planetary nebulae, and existing limits on the S IV 10.5μ line flux from Sgr A do not preclude the possibility that some of the 10μ continuum sources are planetary nebulae (Bregman and Rank 1975).

Conclusions

High-resolution spectra of the Ne II 12.8μ fine-structure line in emission from the galactic center cloud Sgr A West show a velocity dispersion of several hundred km s^{-1} and a line-center LSR radial velocity of $+75 \pm 20 \text{ km s}^{-1}$ independent of position. The line profile is unlikely to be significantly affected by intervening material. Hence it appears that there is systematic motion of the ionized gas component of the galactic center cloud with respect to the massive stellar component of material at the galactic center. An upper limit of $\sim 4 \times 10^6 M_{\odot}$ for the mass within 0.8 parsecs

of the galactic center is obtained from the velocity dispersion.

TABLE 1

Total flux in the Ne II line for various beam positions shown in Figure 2. Errors on detected fluxes are $\pm \sigma$; upper limits are 3σ .

TABLE 1

Position	Beam size	Flux ($10^{-17} \text{ W/cm}^{-2}$)
center	16" x 31"	7.0 ± 0.3
north	"	2.8 ± 0.3
south	"	2.4 ± 0.6
east	"	1.2 ± 0.5
west	"	< 1.5
north	6" x 14"	1.4 ± 0.3
1	8" diameter circle	1.5 ± 0.3
2	"	1.5 ± 0.3
3	"	1.2 ± 0.3
4	"	1.6 ± 0.3
5	"	< 0.9
6	"	< 0.9

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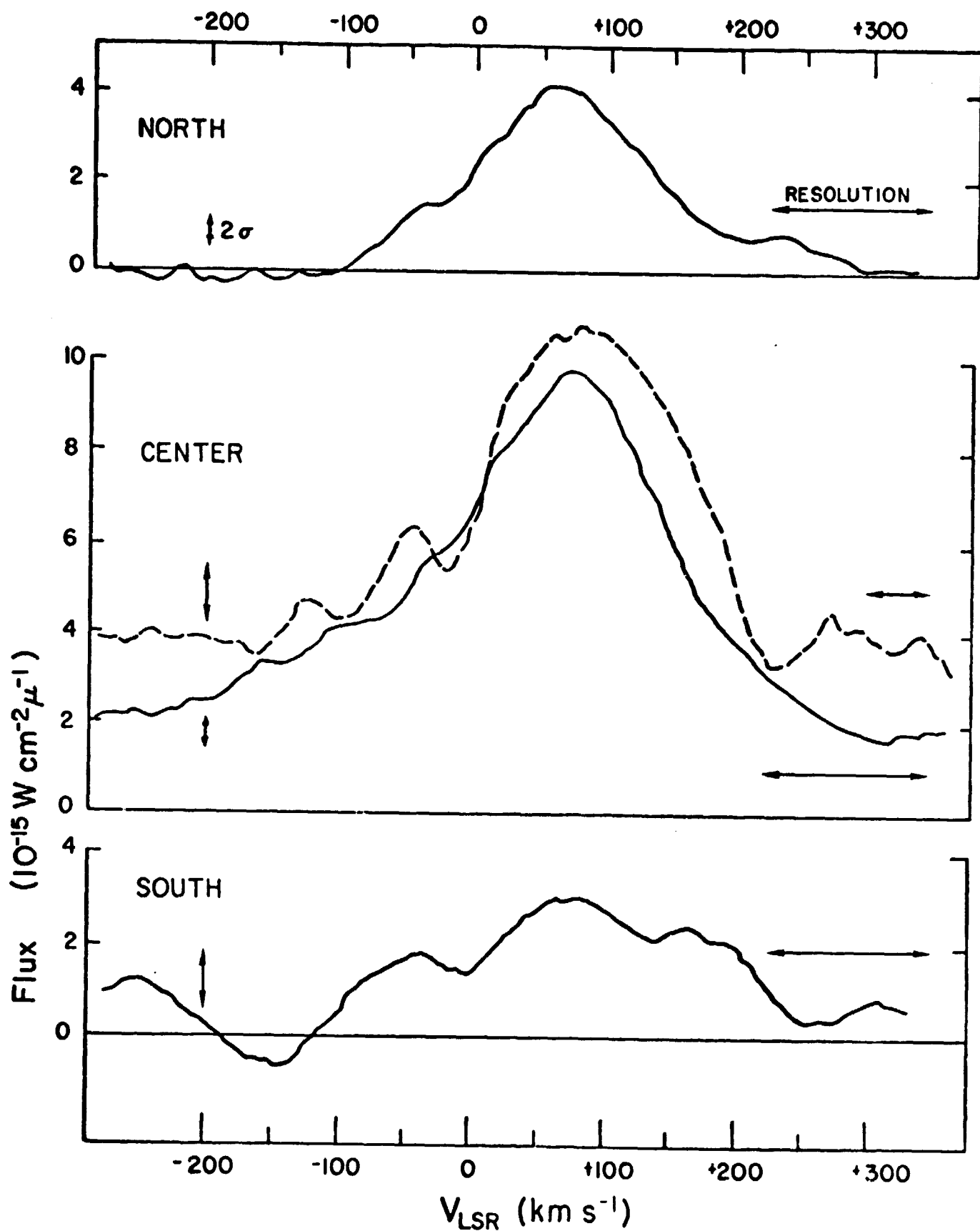
FIGURE CAPTIONS

Figure 1: Spectra of the 12.8μ Ne II emission from Sgr A (West) obtained in $16'' \times 31''$ regions centered to the north, on, and to the south of the 10μ source IRS 1 (see figure 2). The solid-line and dashed-line spectra were obtained with resolution of 0.30 cm^{-1} and 0.10 cm^{-1} respectively. The error bars represent 2σ statistical fluctuation after smoothing the data over the resolution. The apparent discrepancy in continuum flux between the two spectra of the central region reflects a susceptibility of the spectrometer and electronics to small DC offsets which alter the zero level but do not affect the shape of the spectra or the flux scale.

Figure 2: Beam positions listed in Table 1 superimposed on the 10μ continuum map of Becklin and Neugebauer (1975). Since the Coudé field rotates during observation, the beam orientations are approximate.

Sgr A (West)

Ne II ($\nu_0 = 780.43 \text{ cm}^{-1}$)



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Figure 1

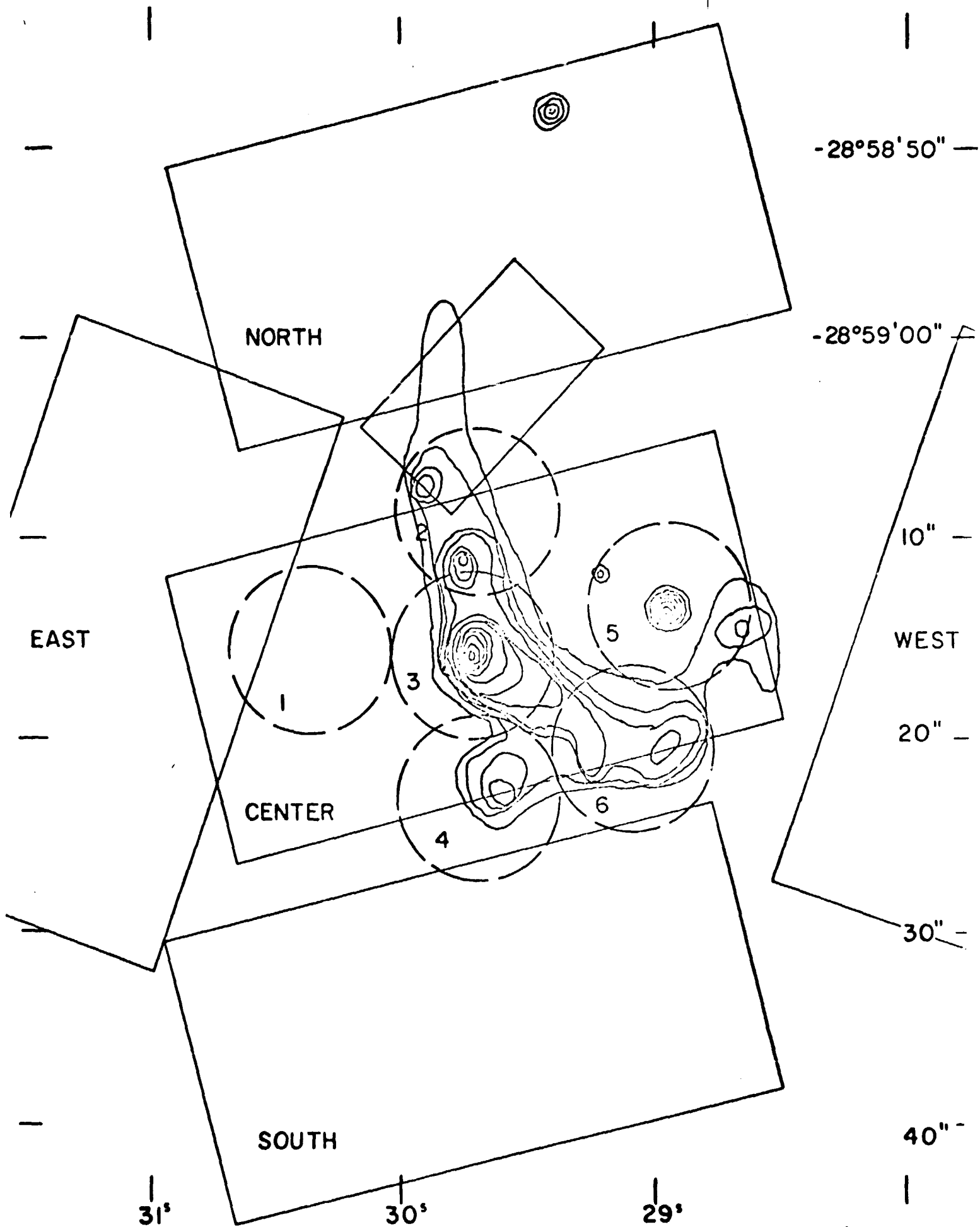


Figure 2